A twenty years progress in QCD in 8 minutes

Comments to the Snowmass theory panel

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QCD

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum \bar{\psi}_i (i\hat{D} - m_i)\psi_i$$

Mass gap = 1 000 000 USD

Progress in establishing the existence of the Yang-Mills theory and a mass gap and will require the introduction of fundamental new ideas both in physics and in mathematics.

Hadrons

Chiral perturbation theory
Large-N expansion
Solitons, instantons etc.
Sum rules
HQET, NRQCD

$\Rightarrow$

Partons

Operator product expansion
Perturbation theory
Parton distribution functions
Infra-red safety
Jets

Following suggestion of the organizers, I will structure my comments around three points

1) important breakthroughs in QCD in the past one-two decades;

2) how progress in QCD contributed to progress in high-energy physics;

3) what are potential breakthroughs that can be in anticipated in QCD for the next decade or two.

Breakthroughs in QCD of the past one-two decades

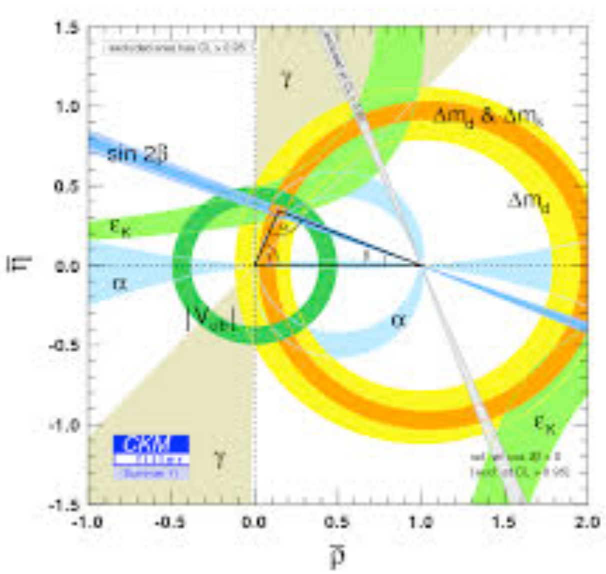
The past two decades was the time of LEP, HERA, B-factories, Tevatron and the first two years of the LHC. Developments in QCD were critical for correct understanding of data from experiments performed at these colliders.

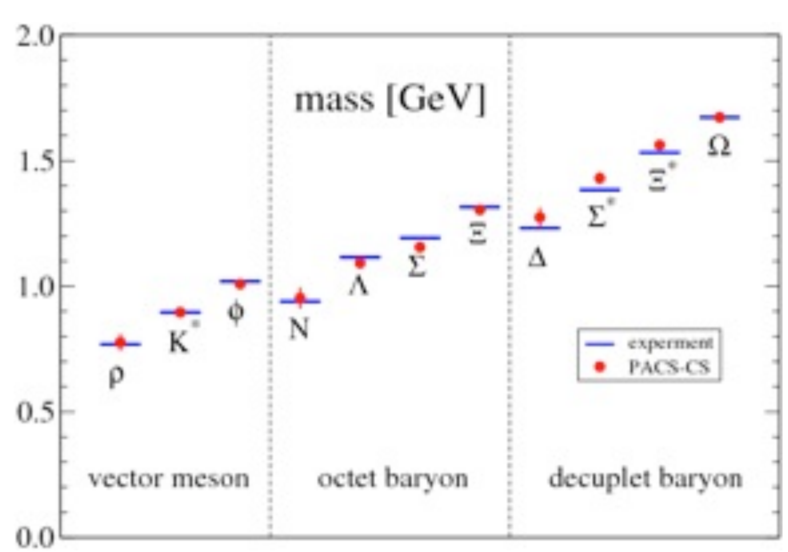
1) successful application of OPE to describe physics of beauty hadrons. An impressive proof of concept of EFTs. Attempts to apply EFT concepts in situations which are beyond direct control of OPE (NRQCD, SCET etc). Proof of the CKM paradigm;

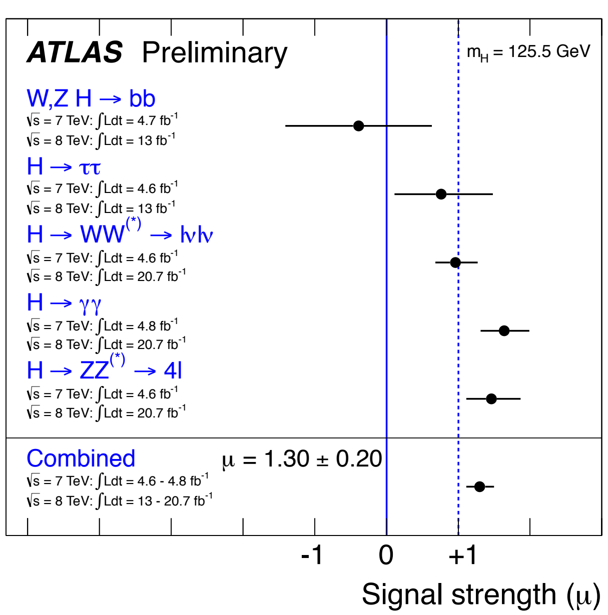
2) lattice QCD started providing reliable results relevant for phenomenology;

3) theoretical supersymmetry for understanding strong dynamics;

4) establishing perturbative QCD as the theory for hadron collisions and for hadroproduction in lepton collisions.







A few remarks on point 4 (pQCD for colliders)

pQCD for colliders went through a dramatic development in the past two decades; we started without knowing much and we have a robust theoretical framework now. To give you a sense of what we learned, let me mention technological developments and physics they enabled.

Technology and tools

spinor-helicity methods
scattering amplitudes (color ordering, recurrences)
infra-red and collinear limits in QCD
parton shower generators
re-summations for soft gluon radiation
CKKW, MLM
one-loop virtual corrections traditional
one-loop virtual corrections unitarity
universal subtraction terms for NLO
NNLO computations for hadron/lepton colliders
integration-by-parts; recurrence relations

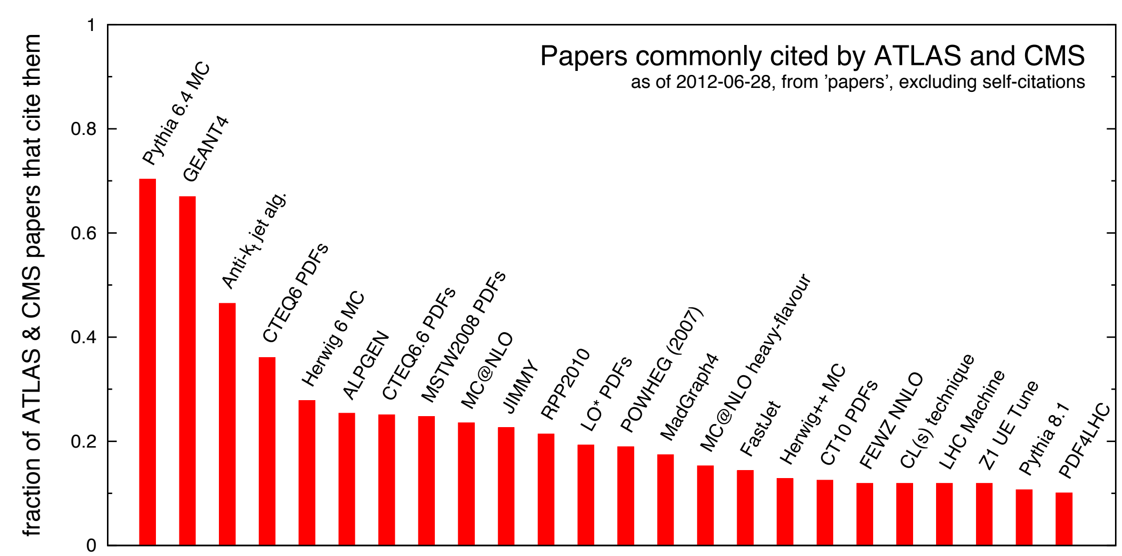
PYTHIA, HERWIG,SHERPA, MADGRAPH, ALPGEN
MCFM, MC@NLO, POWHEG

Physics enabled

jet physics, including substructure techniques
the strong and QED coupling constants
parton distribution functions
W,Z cross-sections and properties
top cross-sections and properties
precision EW (top mass, W mass)
Higgs cross-sections and properties

Smooth, uncontroversial exclusion of New Physics by the run I of the LHC

QCD IN HADRON COLLISIONS



Papers most frequently cited by ATLAS and CMS collaborations (G. Salam).

How progress in QCD contributed to general progress in high-energy physics

Progress in QCD was very essential for helping us to get where we are today in terms of our understanding of particle physics.

All the phenomenological knowledge that we have about Standard Model and how it works (except perhaps of the neutrino physics) is intimately related to either understood QCD or significant developments in perturbative QFTs.

On a more theoretical side:

1) wide acceptance of Effective Field Theories as the result of successes of HQET in B-physics

2) studies of scattering amplitudes grew directly out of attempts of QCD community to provide predictions for collider experiments and perform the required computations efficiently

$$A\left(1^-, 2^+, \ldots, (j-1)^+, j^-, (j+1)^+, \ldots, (n-1)^+, n^+\right) = \frac{\langle 1\ j\rangle^4}{\langle 4\ 5\rangle\langle 5\ 6\rangle \cdots \langle n-1\ n\rangle\langle n\ 1\rangle\langle 1\ 2\rangle\langle 2\ 3\rangle\langle 3\ 4\rangle}.$$

Breakthroughs for the next decade or two?

``It is tough to make predictions, especially about the future". But I will try.

Yoghi Berra

QCD for collider physics

1. Parton showers with quantum interferences;

2. Parton showers with exact leading order matrix elements;

3. Hadronization from first principles;

4. Madgraph@NLO;

5. NNLO for any process and generic understanding of how to organize IR-finite perturbative expansion to any order in perturbation theory;

6. Resummations in the presence of jet algorithms;

7. Parton distribution function with controllable errors from lattice calculations.

Will we be able to do precision physics at hadron colliders at the level which is far beyond of what we are capable to do today?

Breakthroughs for the next decade or two?

Perturbative QFT

1. Generalized unitarity at two- (and more) loops for multi-leg integrals;

2. Two- and more-loop Feynman integrals for real-life applications made easy (or trivial);

3. very clever Laporta (integral reduction) algorithm;

4. Numerical evaluation of multi-loop divergent Minkowski integrals made practical, convenient and fast.

Will modern developments in understanding of scattering amplitudes help in making non-supersymmetric pQFTs significantly simpler to deal with?

Low-energy QCD and physics of the Standard Model

1. Large-N QCD analytically will be solved. Lattice QCD will become a precision tool.

2. Low-energy hadron interactions understood; controllable computations at low-energies are possible.

The problem of light-by-light contribution to muon g-2 is solved both analytically and on the lattice?